

Experimental Analysis of Reduced-Sized Coplanar Waveguide Transmission Lines

George E. Ponchak

NASA Glenn Research Center, 21000 Brookpark Rd., MS 54/5, Cleveland, OH, 44135

Abstract — An experimental investigation of the use of capacitive loading of coplanar waveguides to reduce their line length and, thus the size, of monolithic microwave integrated circuits is presented. The reduced sized coplanar waveguides are compared to unloaded transmission lines and to lumped element transmission line segments. The phase bandwidth, defined by 2 percent error in S_{21} , and the return loss bandwidth, defined by a return loss greater than 15 dB, of coplanar waveguides reduced from 0 to 90 percent are compared, and the insertion loss as a function of the size reduction is presented.

I. INTRODUCTION

Radio Frequency and Microwave Monolithic Integrated Circuits (RFICs and MMICs) fabricated on Si, GaAs, and InP substrates have obtained widespread use in personal communication, GPS, and other systems that are highly dependent on cost. Thus, there is a great desire to reduce the size of MMICs to increase the number of circuits per wafer, and thus lower manufacturing cost. The traditional method of reducing the circuit size in RFICs is to use an all lumped element design whereby all matching and filter circuits are comprised of multi-turn inductors and capacitors. However, multi-turn inductors have a low quality factor, which increases insertion loss, and lumped element designs are narrow band. In the past, MMIC designs avoided the use of inductors because of these losses and the inductor's high parasitic capacitance, which results in a low self-resonant frequency, by using transmission line segments. However, high Q, lumped element capacitors are relatively easy to make and are widely used in MMIC designs.

Reactive loading of a transmission line to increase its electrical length or to enable a reduction of the lines physical length for a desired electrical length is another alternative. Capacitive loading of a shorter section of higher impedance transmission line has been used to replace the quarter-wavelength sections of branch-line [1], rat-race [1], and Wilkinson power dividers [2]. However, the technique has not been widely used, especially for non-quarter-wavelength transmission lines.

In this paper, reduced length finite ground coplanar (FGC) waveguide transmission lines are experimentally characterized. Specifically, transmission lines with

electrical length ranging from 22.5 to 135° at 10 GHz are reduced from 0 to 90 percent. Measured characteristics are compared to theoretical characteristics.

II. CIRCUIT DESIGN

The schematic representation of a transmission line of electrical length θ_0 and Z_0 is shown in Fig. 1a, and the capacitively loaded, reduced length transmission line is shown in Fig. 1b.

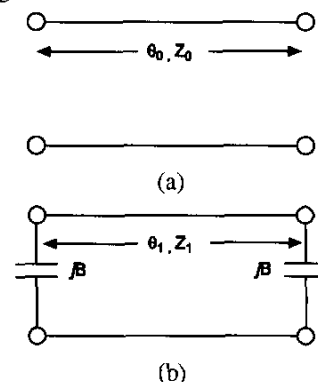


Fig.1: Schematic of (a) full sized transmission line and (b) capacitively loaded, reduced sized transmission line.

Because FGC is a uniplanar transmission line, it is easy to integrate series and shunt components without via holes. Thus, in theory, we can use inductive or capacitive loading, but, as already mentioned, inductors are low Q devices that should be avoided. Therefore, only capacitive loading will be considered.

The theoretical derivation of the equivalence between the circuits in Figs. 1a and 1b has been shown in a series of papers on loaded-line phase shifters [3-9]. However, in these papers, the intent was to derive an optimum electrical line length, θ_1 , for phase shifters. Here, the intent is to determine the bandwidth and insertion loss for reduced sized CPW transmission lines as a direct replacement of full length CPW transmission lines.

The design equations are:

$$Z_1 = Z_0 \frac{\sin(\Theta_0)}{\sin(\Theta_0 - \Delta)} \quad (1)$$

$$\omega CZ_0 = (1 + \frac{Z_0}{Z_1}) \tan(\frac{\Delta}{2}) \quad (2)$$

(1) and (2) are in a form that permits the determination of the reduced sized transmission line characteristic impedance and the loading capacitor for a desired electrical length, θ_0 , characteristic impedance, Z_0 , and line length reduction, $\Delta = \theta_0 - \theta_1$. Since it is desired that the reactive loading be capacitive, Δ must be less than π (180°) as seen in (2). (1) shows that Δ cannot equal θ_0 , or 100 percent reduction is not possible. Design curves derived from (1) and (2) are shown in Fig. 2. In Fig. 2a, a reference line at $Z_1/Z_0 = 0.7$ is shown because this is the lower limit for many transmission lines. For example, if $Z_0 = 50 \Omega$, $Z_1 = 35 \Omega$, which is the lower limit for CPW lines before the slot width becomes very narrow. A reference line is also seen for $Z_1/Z_0 = 2$, which is the upper limit for CPW lines before the center conductor becomes too narrow. Fig. 2a shows that the shortened transmission line characteristic impedance is less than Z_0 for a range of Δ and θ_0 , and because of restrictions on Z_1 , equivalent transmission lines with θ_0 greater than 135° are not practical with the single section shown in Fig. 1b.

III. CIRCUIT FABRICATION AND CHARACTERIZATION

The circuits are fabricated on silicon wafers with a resistivity of $2500 \Omega \text{ cm}$ using standard integrated circuit processing. The capacitors are metal-insulator (2000 \AA Si_3N_4)-metal structures with an airbridge connection between the CPW center conductor and the capacitor, which is fabricated on the CPW ground planes. The CPW lines have a center conductor width, S , of $94 \mu\text{m}$, a slot width, W , of $59 \mu\text{m}$, and a ground plane width of $280 \mu\text{m}$. These CPW lines have a characteristic impedance, Z_0 , of 50Ω . The sections of line in the reduced length sections, θ_1 , are designed to yield the required Z_1 while maintaining the $S+2W=212 \mu\text{m}$.

A full TRL calibration was performed using standards fabricated on the same wafer as the test circuits. The reference planes are at the loading capacitors. All measurements were made on an HP 8510C vector network analyser and Picoprobe RF probes.

IV. RESULTS

Typical measured characteristics of reduced sized transmission lines are shown in Figs. 3 and 4. As shown in Fig. 3, the return loss characteristics are degraded as Δ is increased, and the bandwidth for $|S_{11}| < -15 \text{ dB}$ decreases as Δ increases. Figs. 3 and 4 also show that the reduced sized transmission line has a low pass characteristic with

a ripple in the pass band and a transmission pole at the design frequency of 10 GHz.

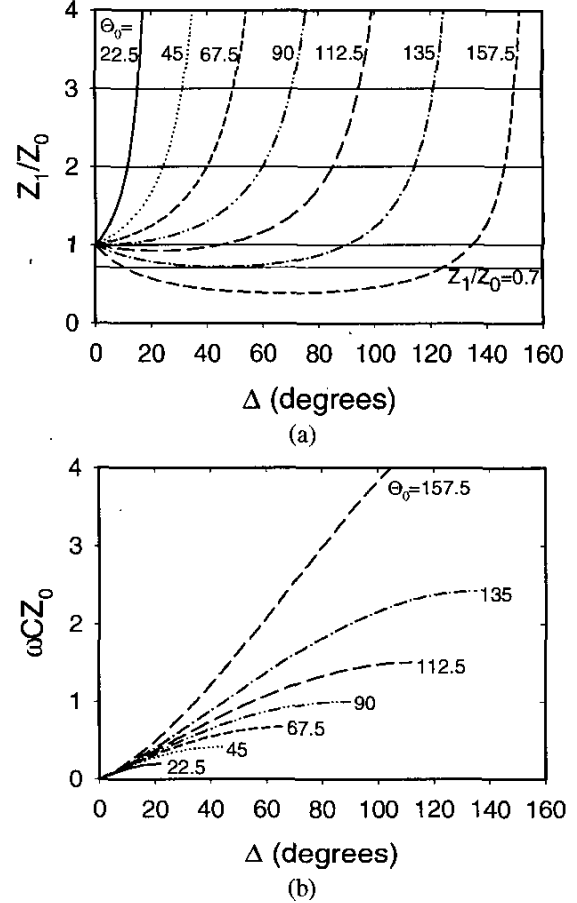


Fig. 2: Design curves for reduced length transmission lines.

For the reduced sized CPW lines to replace full sized CPW lines, a reasonable design criteria is a phase error of less than 2° for the reduced sized CPW line compared to the full sized CPW line and a return loss greater than 15 dB. These design rules are used to compare the characteristics of all of the test cases and are shown in Figs. 5 and 6, which show the ratio of the upper frequency that meets the design criteria to the design frequency as a function of Δ . Figs. 5 and 6 also show the theoretical bandwidth calculated from ideal circuit analysis. The 15 dB bandwidth decreases smoothly and monotonically as Δ increases for the data shown, but it must be noted that for small Δ , the return loss is greater than 15 dB from 0 GHz to the values shown in Fig. 5. However, for large Δ , the $|S_{11}|$ increases below the design frequency and the usable bandwidth does not extend to 0 GHz (see Fig. 3). Similar characteristics apply to the 2° bandwidth shown in Fig. 6. Thus, there are discontinuities in the 2° bandwidth results shown in Fig.

6. The bandwidth of reduced sized transmission lines as $\Delta \rightarrow \theta_0$ approaches the theoretical bandwidth of an ideal lumped element circuit design as shown in Fig. 5. The agreement between measured and theoretical results is good, especially for $|S_{11}|$ which is easier to measure accurately.

The ratio of the measured insertion loss for the reduced sized CPW lines to the full length CPW line is shown in Fig. 7. Except for the single point for $\theta_0=45^\circ, \Delta=20^\circ$, all of the data appears to follow a linear relationship through $\Delta=100^\circ$. The $\theta_0=45^\circ$ insertion loss was very small, less than 0.04 dB, and thus, susceptible to errors in measurement. Evaluation of Figs. 5 through 7 indicates that transmission line length may be greatly reduced, but a penalty in bandwidth and insertion loss is the cost. However, the bandwidth is large enough for most circuit applications if Δ is less than 30° , and greater than the bandwidth of lumped element circuits. Also, although the insertion loss of reduced sized CPW lines can be twice the full length insertion loss, the real increase in insertion loss is only 0.3 dB for the worst case ($\theta_0=135^\circ$ and $\Delta=100^\circ$).

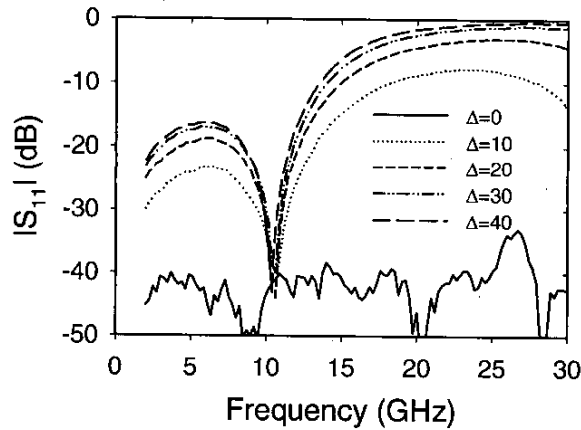


Fig. 3: Measured $|S_{11}|$ as a function of frequency for reduced sized transmission lines with θ_0 equal to 90° .

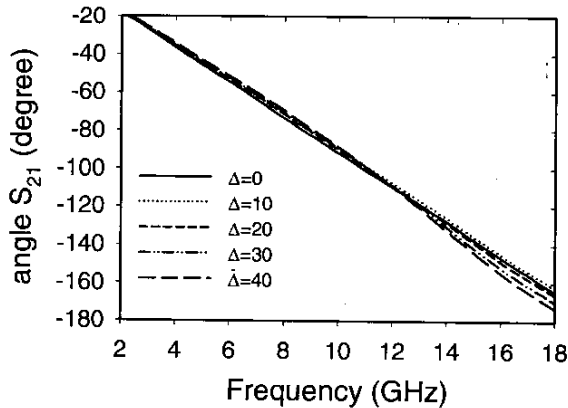


Fig. 4: Measured angle of S_{21} as a function of frequency for reduced sized transmission lines with θ_0 equal to 90° .

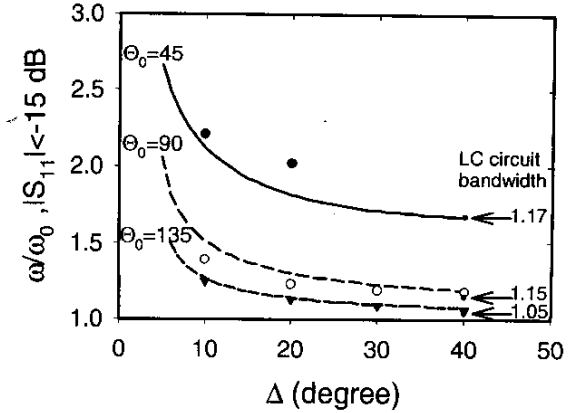


Fig. 5: Theoretical and measured $|S_{11}|$ bandwidth of reduced sized transmission lines as a function of Δ (symbols are measured points and curves are theoretical).

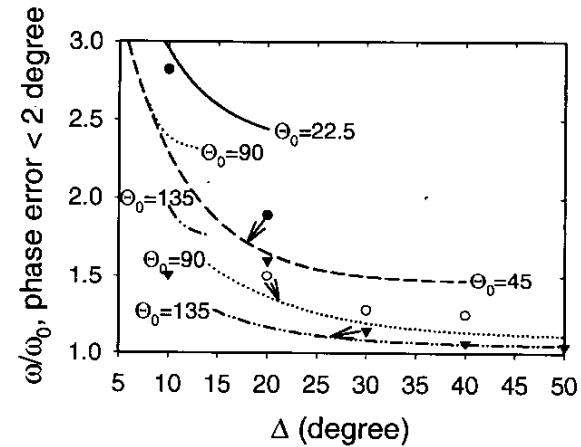


Fig. 6: Theoretical and measured 2° bandwidth of reduced sized transmission lines as a function of Δ (symbols are measured points and curves are theoretical).

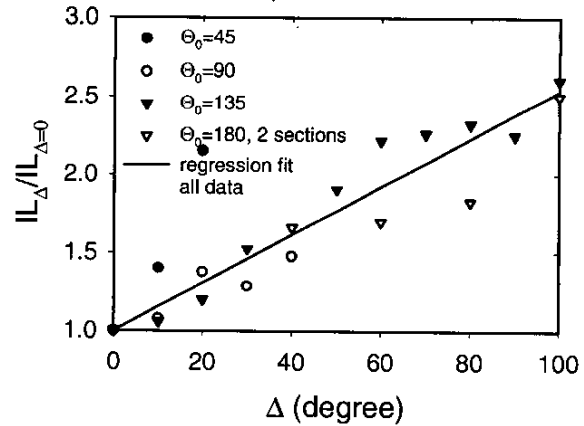


Fig. 7: Measured insertion loss at 10 GHz as a function of Δ normalized to the insertion loss of full length CPW.

(1) and (2) show that a single section of reduced sized transmission line, as shown in Fig. 1b, cannot be used for

$\theta_0=180^\circ$. Instead, a two section line as shown in Fig. 8 can be used. In fact, a two section circuit can be used for all cases.

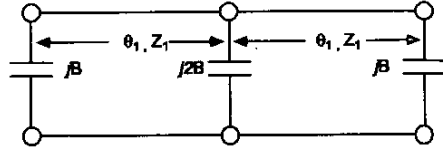


Fig. 8: Schematic of two section, reduced length CPW line.

A $\theta_0=180^\circ$, two section circuit was built and characterized. The measured characteristics are shown in Figs. 9 and 10. The 15 dB and the 2° bandwidths are indicated on the two figures. The bandwidth is larger than the $\theta_0=135^\circ$, single section circuit for the full range of Δ . The insertion loss is plotted on Fig. 7, where it is seen that it follows the same linear relationship as the single section circuits.

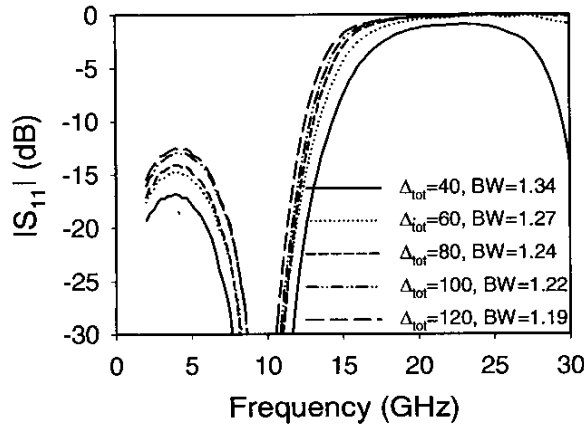


Fig. 9: Measured $|S_{11}|$ as a function of frequency for $\theta_0=180^\circ$, two section reduced length CPW line.

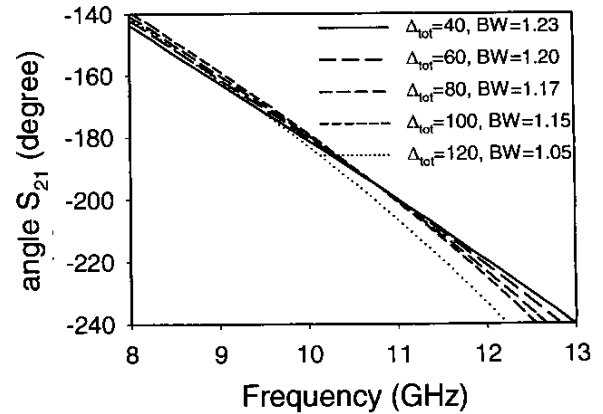


Fig. 10: Measured angle of S_{21} as a function of frequency for $\theta_0=180^\circ$, two section reduced length CPW line.

V. CONCLUSIONS

Measured and theoretical characterization of reduced length CPW lines shows that they are a good alternative to lumped element circuit designs. Compared to full sized CPW lines, the bandwidth decreases and the insertion loss increases as the length reduction increases, but they are better than lumped element circuits.

REFERENCES

- [1] T. Hirota, A. Minakawa, and M. Muraguchi, "Reduced-size branch-line and rat-race hybrids for uniplanar MMIC's," *IEEE Trans. Microwave Theory and Tech.*, Vol. 38, No. 3, pp. 270-275, March 1990.
- [2] M. C. Scardelletti, G. E. Ponchak, and T. M. Weller, "Miniaturized wilkinson power dividers utilizing capacitive loading," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 1, pp. 6-8, Jan. 2002. (correction in *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 4, pp. 145, April 2002).
- [3] A. J. Simmons, "Phase shift by periodic loading of waveguide and its application to broad-band circular polarization," *IRE Trans. Microwave Theory and Tech.*, pp. 18-21, Dec. 1955.
- [4] J. F. White, "High power, p-i-n diode controlled, microwave transmission phase shifters," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-13, pp. 233-242, March 1965.
- [5] F. L. Opp and W. F. Hoffman, "Design of digital loaded-line phase-shift networks for microwave thin-film applications," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-16, No. 7, pp. 462-468, July 1968.
- [6] T. Yahara, "A note on designing digital diode-loaded-line phase shifters," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-22, pp. 703-704, Oct. 1972.
- [7] R. V. Garver, "Broad-band diode phase shifters," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-20, No. 5, pp. 314-323, May 1972.
- [8] W. A. Davis, "Design equations and bandwidth of loaded-line phase shifters," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-22, pp. 561-563, May 1974.
- [9] H. A. Atwater, "Circuit design of the loaded-line phase shifter," *IEEE Trans. Microwave Theory and Tech.*, Vol. MTT-33, No. 7, pp. 626-634, July 1985.